Colored mulch for food crops

Light reflected upward from a new red plastic mulch acts through a plant's natural phytochrome system to regulate products of photosynthesis and increase yield and quality of food crops, with worldwide implications.

Michael J. Kasperbauer

Plastic mulches have been used for many years in field production of food crops such as tomato and strawberry. They conserve water by blocking rapid evaporation from the soil surface; control weeds, reducing herbicide use; and keep soil from splashing onto the fruit. Applying water through drip-irrigation tubes located below the mulch can provide enough water for optimal growth and avoid nutrient leaching caused by excessive rainfall.

Black is the most widely used color of plastic mulch. We hypothesized that a change of mulch color could preserve the basic benefits while also reflecting yield- and quality-enhancing morphogenic light to the growing plants. The hypothesis was correct, and colored-mulch technology is now manufactured by a Fortune 500 company and marketed internationally as Selective Reflective Mulch. We can now grow food crop plants in sunlight over a mulch that reflects a light signal from the soil surface to the developing plant; the signal activates a natural growth regulatory system that tells the plant how to allocate its new growth to affect yield, flavor, and nutrient quality. How did the theory and developmental steps evolve?

Curiosity about plant growth

Although I did not realize it at the time, the first step on the road to development of colored-mulch technology began with my childhood observations of weed seedlings growing on an Iowa farm more than a half century ago. It was obvious to me that newly emerged pigweed seedlings developed short, thick stems and massive roots if they were far from other plants, whereas closely spaced seedlings had less massive roots and were taller. It was as though they sensed competition and responded by growing taller to keep the leaves in sunlight. That growth pattern was detectable among the crowded seedlings even before they were large enough to shade each other, suggesting that the signal was something other than shade per se. My curiosity about the difference in growth patterns led to many questions, but no one had the answers at that time.

When I was in graduate school at Iowa State University in the late 1950s, we made good progress on season recognition by biennial sweetclover, a legume used as a soil-improvement crop. During the first year, it made mostly shoot growth during long days of spring, but as day length shortened in autumn, the shoots stopped growing and the taproots enlarged rapidly. That study provided information on seasonal growth patterns and maximizing its use as a soil-improvement legume, but we did not learn anything about the sensor within the growing plant that could recognize seasons and change the priority of growth from shoots to roots.

Basic research on control mechanisms

During that same period, a research team led by Sterling Hendricks and Harry Borthwick at the U.S. Department of Agriculture–Agricultural Research Service (USDA–ARS) Pioneering Research Laboratory for Plant Physiology at Beltsville, MD, identified a photoreversible growth regulatory system that they called phytochrome. They visualized a pigment that existed in two forms. One form absorbed red light (R) and became the far-red-absorbing form (Pfr), which then absorbed far-red (FR, wavelengths just beyond visible red) and reverted to the red-absorbing form (Pr). They concluded that Pfr was biologically active in promoting seed germination and in inhibiting the flowering of short-day plants such as soybean and chrysanthemum (*1*).

After completing my Ph.D. in plant physiology at Iowa State in 1961, I did postdoctoral research at the Pioneering Research Laboratory with Hendricks and Borthwick. The first year, I was a National Science Foundation postdoctoral

The author is with the U.S. Department of Agriculture.

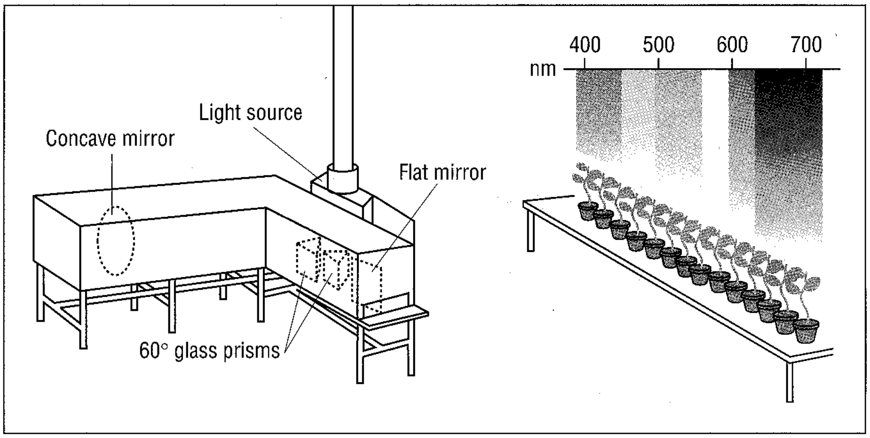


Figure 1. **Diagram of the Hendricks-built spectrograph showing the path of light from a carbon arc through prisms to the treatment table.**

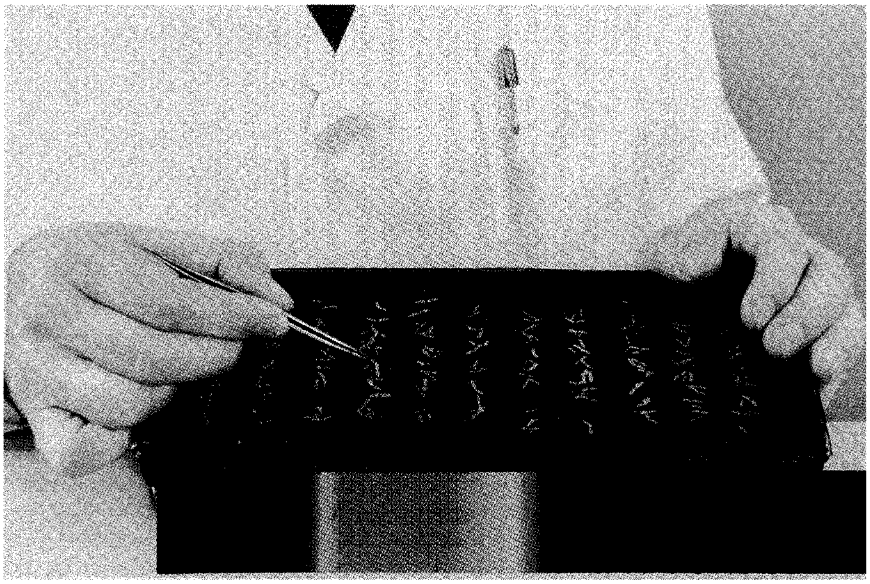


Figure 2. **A tray of chenopodium seedlings ready for treatment on the spectrograph.** The spectrum is superimposed to show that each row received a slightly different color.

fellow; and the second year, I was the National Academy of Science–National Research Council resident research associate at the lab. Although the focus of the research group was the chemical basis of phytochrome action in control of the flowering process, I was able to do some basic studies of plant developmental responses to different wavelengths (colors) with the specialized equipment.

Within a few days of my arrival in Beltsville, Hendricks demonstrated the spectrograph that he had designed and built from spare, surplus, and borrowed parts in the 1940s (Figure 1). The surplus 12-kW carbon arc light source had served as the spotlight at a nearby vaudeville theater in the early 1900s. The light was beamed through a narrow vertical slit and through two large prisms that were borrowed from the Smithsonian, where they had been stored after being used by Samuel Pierpont Langley (1834–1906), a noted astronomer, physicist, and aeronautics pioneer. The "rainbow" of colors was displayed on the table where Hendricks, Borthwick, and colleagues had treated many soybean and other test plants to determine effectiveness of different colors of light en route to the discovery of phytochrome.

Following that fascinating demonstration, I asked whether they would consider smaller test plants to get more data points and even greater precision, which might provide clues for possible use in future field crop production systems. It was a natural question, because I had already observed that an Iowa strain of pigweed could be induced to flower at less than 1.5 cm tall on short days, whereas it would grow to more than a meter tall without flowering on long days. Within a few days, Borthwick found a small seed supply of a related weed species, *Chenopodium rubrum*. Exploratory experiments were done to compare early responsiveness of pigweed, chenopodium, and a few other species. The pigweed and chenopodium were about equal, but the available chenopodium seed supply was greater. Pretreatment, treatment, and post-treatment protocols were developed for chenopodium as a tiny test plant for use on the spectrograph. That included development of a numerical rating scale based on microscopic viewing of the shoot apex of each plant and determining its stage of development a week after completion of treatment on the spectrograph. A tray of chenopodium seedlings ready for treatment on the spectrograph is shown in Figure 2. Use of the chenopodium plants allowed us to move the "treatment table" closer to the light source and to obtain greater precision.

During the next year and a half, we conducted many experiments to test different exposure durations, energy

Figure 3. **The author with Sterling Hendricks (right) in a 1963 photograph.**

levels, timing of dark-reversion of phytochrome, and efficiency of different wavelengths (colors) of light. All three of us were actively involved in design, conduct, and interpretation of every experiment with chenopodium on the spectrograph. Very quickly, we developed what has been described as the most precise action spectrum (efficiency of different wavelengths of light) ever obtained for phytochrome control of flowering (*2, 3*).

Another important benefit of doing research on the spectrograph with Hendricks and Borthwick was that we had time for informal discussions including some "what if" scenarios while we waited for completion of plant exposure times of 10 to 15 min, or longer, in the spectrum. One day, I asked "what if" the light impinged on the lower rather than on the upper surface of the leaf. Initially, Hendricks dismissed it as unrealistic; however, Borthwick had a few extra cocklebur plants, and I conducted a small-scale "curiosity" experiment. The plant response was the same no matter which surface received the light. Although that experiment seemed somewhat unconventional in 1962, it did become highly relevant about 22 years later when my colleagues and I began researching the possible plant growth-regulating effects of upwardly reflected light over different colored soils or dead plant residue in conservation tillage systems.

Even though the spectrograph experiments with chenopodium focused on photoreversible phytochrome control of flowering (action peaks for R and FR were about 660 and 730 nm, respectively), I also recorded unexpected plant responses that were not part of the designed experiment. One such observation was a stem elongation and raised leaf angle response to prolonged exposure to FR at longer wavelengths than were thought to be effective via phytochrome at that time (1962). That notation of a seedling growth response at 750 to 770 nm on the spectrograph became a key step in understanding phytochrome sensing of competition and regulation of growth processes in sun-grown plants in the late 1960s and in development of the reflection spectrum for colored-mulch technology in the early 1990s.

In a 1963 photograph, Hendricks and I are shown (Figure 3) discussing whole-plant phytochrome research in a greenhouse at Beltsville. Although we made considerable progress on phytochrome control of floral induction in the previous two years, we had absolutely no idea that the "curiosity" experiment (test plants responded the same to color of light impinging on either the upper or the lower surface of a leaf) and the observation of morphological responses to longer wavelengths of FR would become the foundation of colored-mulch technology that would be developed 25 to 30 years later.

Controlled environments and field plots

My USDA–ARS career began in 1963 as a research plant physiologist in the Crops Research Unit at Lexington, KY. We conducted laboratory, controlled-environment, and field studies designed to improve plant-to-plant uniformity to facilitate production efficiency. The work included phytochrome regulation of photosynthate partitioning and leaf chemistry.

The controlled-environment studies showed that while R applied near the middle of the night was critical for "on–off" control of floral induction, FR during the day was extremely important in the physical development of growing plants. A higher FR/R photon ratio near the end of each day resulted in seedlings with longer stems, higher leaf angles, larger leaf areas, thinner leaves, modified chloroplast structure, altered concentration of photosynthetic pigments, a higher shoot/root biomass ratio, and modified chemical composition. Many of the responses to FR/R photon ratios in controlled environments are now highly relevant to our work with color (primarily, the reflected FR/R ratio) in regulation of yield and quality of sun-grown food crops. For example, the higher sugar content in plants that received a higher FR/R ratio during the day was only of academic interest when published in 1970 (*4*), but it is now highly relevant when growing food crops such as strawberry over FR-reflecting mulch.

In general, extra FR applied in the controlled environments resulted in plants that were very similar to closely spaced plants grown outdoors, even before the outdoor plants were large enough to shade each other. (The long-awaited answer to my childhood questions about seedling growth response to competition was about to come into focus.) In the late 1960s, it became apparent to me that FR transmitted through and/or reflected from nearby green plants was the dominant variable in phytochrome sensing of plant competition and regulation of plant development to favor survival among the perceived competition (5). A developmental response to wavelengths of FR reflected from green leaves before the seedlings were large enough to shade each other was also consistent with the earlier notation of unexpected stem elongation and leaf angle responses to the longer wavelengths of FR, as was observed on the spectrograph and discussed earlier in this article.

FR reflected from growing plants

Before I transferred to South Carolina in 1983, soil scientist Patrick G. Hunt and colleagues had found that soybean yields were inexplicably higher in north–south rows when they were irrigated and higher in east–west rows when there was occasional water stress. In an early discussion with Hunt, I recalled my controlled-environment experiments at Kentucky in which seedlings that received a higher FR/R ratio at the end of each day partitioned more growth to shoots and less to roots (5). With a new portable spectroradiometer, we measured reflection percentages at different wavelengths from green soybean leaves and found that they reached a maximum at about 750 to 760 nm (which was the exact wavelength range that had altered stem and leaf growth responses to prolonged FR on the Beltsville spectrograph in 1962). We also measured spectra of light coming to the upper parts of plants and found that those in north–south rows received more FR reflected from adjacent rows and higher FR/R photon ratios near the end of the day. A companion controlled-environment study showed that the same cultivar of soybean did indeed partition more growth to shoots and less to roots if it received the higher FR/R ratio at the end of each day.

The directional FR reflection from soybean leaves was attributed to heliotropic (sun-tracking) leaves. The 1984 paper launched international awareness of the importance of reflected FR in field crop production (6). Other studies dealing with FR reflection from growing plants and effects on tillering (branching), growth, and yield were done with wheat, corn, and soybean in 1984 and 1985. They all showed that FR reflected by green leaves on nearby plants affected the FR/R ratio enough to affect growth and yield.

Reflection from the soil surface

Next, we decided to measure the spectra of light reflected from different kinds of dead plant residues used in conservation tillage systems. This was extended to reflection from different-colored soils. As had been observed when the reflection was from growing plants, a higher reflected FR/R ratio resulted in taller seedlings and a higher shoot/root weight ratio. A lower FR/R ratio resulted in more massive roots and a lower shoot/root weight ratio.

When it was apparent that seedlings of many different plant species responded to color of upwardly reflected light over different colored soils and plant residues, the studies expanded to painted panels. In addition to allowing more flexibility in selection of colors, the painted panels were better suited for outdoor experiments, because soil and dead plant residue washed away or changed color when it rained. Plants responded the same way to a given reflection spectrum whether they were over soil-covered or painted panels (7).

Colored-mulch technology

In 1986, Dennis Decoteau, a new horticulturist at the nearby Clemson Pee Dee Research Center, asked if he could join us for a tomato field test. Tomato was an ideal choice, because we had already tested R–FR photoreversible control of phytochrome-regulated tomato seedling growth in a controlled environment. When all of the seedlings received the same amount of photosynthetic light, those that received a higher FR/R photon ratio developed larger shoots and a higher shoot/root weight ratio (Table 1). Seedlings that received a few minutes of R immediately after the FR remained smaller and grew at the same rate as those that did not get FR. The strong photoreversible control by phytochrome indicated a high probability that tomato plants would be responsive to the FR/R photon ratio reflected up to the growing plants from the soil surface.

We used standard black plastic mulch over trickle irrigation tubes as the control treatment. A range of upwardly reflected spectra was obtained by painting some of the plastic. Early crop yields were higher over red-painted plastic than over the standard black. However, we quickly found in subsequent experiments that the yield response sometimes differed over red paints that looked the same but reflected different amounts of FR. That is, they reflected the same wavelengths in the visible part of the spectrum but different wavelengths in the invisible FR portion.

Many different colors of paint were examined for reflection spectra, and those reflecting a desired range of FR/R ratios were applied to plastic sheets and field tested with several shoot and root crops. The exterior paints were ideal for small plot studies that involved many colors. However, the reflection spectrum of each batch of each color of paint had to be confirmed before we could interpret the results. This confirmation was critical in the developmental stage, because two batches of the same

***Table 1.* Size of tomato seedlings that received the same photosynthetic light ending with R or FR (low or high FR/R photon ratios, respectively) in a controlled environment each day for 3 weeks**

Plant part	End-of-day color (FR/R photon ratio) R (Low)	FR (High)	FR, R (High, low)
Leaflet			
wt, mg	5691 b	6159 a	5710 b
area, cm^2	223 b	273 a	227 b
wt/area, mg/cm^2	25.6 a	22.6 b	25.2 a
Stem length, cm	8.3 b	10.5 a	8.5 b
Shoot wt, g	10.79b	11.79a	10.81b
Shoot/root wt ratio	2.39b	2.63a	2.38b

Values are means per plant, and those followed by the same letter within a row do not differ at $p = 0.05$. The R and FR treatments were applied for 5 min at the end of each day as described in Reference 5. This is the standard test of R–FR photoreversibility and phytochrome control of seedling morphology. Source: Data are from a 1985 test of tomato seedling responsiveness to R and FR.

Figure 4. **Field plots showing turnip (a root crop) and tomato (a shoot crop) growing over a range of mulch colors.**

Figure 5. **Tomatoes growing over the red plastic mulch.** Also see Table 2.

Figure 6. **Strawberries growing over red and standard black plastic mulch.** Also see Table 3.

color could reflect identically in the visible part of the spectrum but differently in the FR portion. Thus, two painted surfaces that appeared identical could reflect different FR/R ratios and give different plant responses. Typical field studies with a root crop (turnip) and a shoot crop (tomato) are shown in Figure 4.

Patent applications for the colored-mulch technology were filed after we were convinced that upward reflection from the soil surface could act through natural morphogenic pigments within growing plants to affect photosynthate allocation among developing parts (i.e., yield). The technology was licensed to Sonoco Products Co. of Hartsville, SC, and a cooperative research and development agreement was established between ARS and Sonoco to facilitate development of the technology. This involved preparation of a suitable reflection spectrum for yield of crops such as tomato and strawberry. That theoretically ideal reflection spectrum was based on my career research up to that time. In cooperation with Sonoco, the next step was to work with pigment chemists to develop a light-stable, nontoxic pigment combination that reflected the desired spectrum. This resulted in development of a red plastic that reflects a spectrum favoring yield of tomato and strawberry under field conditions (Figures 5 and 6; Tables 2 and 3). Both crops developed larger fruit and higher yields over red plastic mulch than over the stan-

Table 2. **Tomato yield during the first 2.5 weeks over red or black plastic mulch**

	Yield per 48 plants		
Mulch color	kg	Number of fruit	g/fruit
Black	98.9	410	241
Red	127.6	515	248

Source: Adapted from Reference 8.

Table 3. **Strawberry yield from 8 April to 2 May 1997 over red or black plastic mulch**

	Yield per 10 plants		
Mulch color	g	Number of berries	g/berry
Black	1153	70.0	16.5
Red	1606	80.6	19.9

Source: Adapted from Reference 9.

dard black (*8*, *9*). Strawberries grown over the red mulch were sweeter.

What's next?

In addition to effects on yield, we have already shown that light reflected from colored mulches can alter flavor, nutrient, and other quality characteristics of plant products. For example, a few years ago, we used turnip plants to determine whether reflection from different colored mulches could affect the shoot/root weight ratio of sun-grown plants in the field (turnip was selected as the species of choice by the person who realized he would be responsible for digging up the roots). After weighing shoots and roots from several plots, it was obvious that the color of upwardly reflected light influenced shoot and root size. At that point, we decided to find out if it altered the flavor. Surprisingly (at that time), turnip roots from different colored mulches ranged from almost sweet to quite sharp tasting. Those grown with blue plastic mulch developed the sharpest flavor. The next logical step was chemical analyses. Results of cooperative research with a chemist at Kentucky State University indicated that concentrations of flavor components such as glucosinolates and sugars in turnip roots were affected by the color of light reflected to leaves (*10*). The glucosinolate concentration response to color of reflected light may be of more than theoretical interest, because it has been reported that certain glucosinolates or their derivatives may function as protective agents against carcinogens (*11*).

Other studies of quality components are now in progress. Ideally, the next approach would be to expand the flavor and nutrient quality analyses in cooperation with scientists who specialize in specific quality components or crops.

References

(1) Hendricks, S. B. *Cold Springs Harbor Symp. on Quant. Biol.* **1960**, *25*, 245–248.

(2) Kasperbauer, M. J.; Borthwick, H. A.; Hendricks, S. B. *Botan. Gaz.* **1963**, *124*, 444–451.

(3) Kasperbauer, M. J.; Borthwick, H. A.; Hendricks, S. B. *Botan. Gaz.* **1964**, *125*, 79–80.

(4) Kasperbauer, M. J.; Tso, T. C.; Sorokin, T. P. *Phytochemistry* **1970**, *9*, 2091–2095.

(5) Kasperbauer, M. J. *Plant Physiol.* **1971**, *47*, 775–778.

(6) Kasperbauer, M. J.; Hunt, P. G.; Sojka, R. E. *Physiol. Plant.* **1984**, *61*, 549–554.

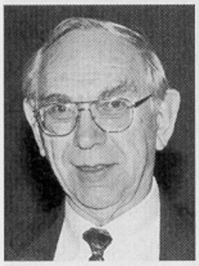
(7) Kasperbauer, M. J.; Hunt, P. G. *Photochem. Photobiol.* **1992**, *56*, 579–584.

(8) Kasperbauer, M. J.; Hunt, P. G. *Crop Sci.* **1998**, *38*, 970–974.

(9) Kasperbauer, M. J. *Crop Sci.* **2000**, *40* (1) in press.

(10) Antonious, G. F.; Kasperbauer, M. J.; Byers, M. E. *Photochem. Photobiol.* **1996**, *64*, 605–610.

(11) Wattenberg, L. W. In *Food and Cancer Prevention: Chemical and Biological Aspects*; Waldron, K. W., Johnson, I. T., Fenwick, G. R., Eds.; Royal Society of Chemistry: Cambridge, U.K., 1993; pp. 12–23.



Michael J. Kasperbauer is a research plant physiologist with the USDA–ARS (Coastal Plains Research Center, 2611 W. Lucas St., Florence, SC 29501-1242; 843-669-5203, ext. 109; kasper@florence.ars.usda.gov). He has a Ph.D. in plant physiology from Iowa State University and did postdoctoral research at the ARS Pioneering Research Lab for Plant Physiology. Much of his research has dealt with light regulation of plant developmental processes from subcellular through whole plant. He has more than 200 publications, has edited and co-authored a book on biotechnology, and has received numerous awards. Those received in the past 10 years include: the Crop Science Research Award and the Seed Science Award from the Crop Science Society of America; the L. M. Ware Research Award in Horticulture; the Agronomic Research Award from the American Society of Agronomy; and the ARS and the Federal Laboratory Consortium Awards for Excellence in Technology Transfer. He was selected Senior Scientist of the Year in 1998 from the South Atlantic Area of USDA–ARS.

"Phytoremeditation?"